RESULTS OF RECYCLER OPTICS FITTING USING LOCO

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Abstract
This report summarizes the results of fitting of Recycler optics model to the orbit response data taken in February and October of 2006 at two settings of the machine working point. The quadrupole gradient errors obtained with this fitting are different from previous results [1]. The problem was tracked down to the fact that kick of some ('LEP-style') correctors used to excite the orbits appears to be 60% off from the design value. The new model presents an improvement in terms of capability to predict the optics performance.

INTRODUCTION

The LOCO (Linear Optics from Closed Orbit) software has been developed by V. Sajaev at ANL and was successfully applied at Accumulator, Debuncher and Tevatron at Fermilab [2-3]. In 2005 M. Xiao created a very detailed lattice file of the Recycler ring and performed first orbit response measurements. The full set of data consisting of roughly 150 orbits was taken on February 25, 2006. The data was then split into 3 sets which were analyzed separately. The found 3 sets of quadrupole errors were different but the values of beta-functions resulting from application of these errors were within 2% from each other (See Figs. 3,4 in Ref. [1]). At that time the nature of large peaks at 630 and 100 locations was not understood.

After the transition to the new betatron tune working point near 0.45 the orbit response measurements were repeated with even larger number of orbits taken, about 200. Interestingly, the fit convergence with the new data was worse, the r.m.s. orbit difference between the measured and model orbit was about 20μm as compared with 9μm in February data. The new settings of the trim quadrupole currents being substituted into the February model produced beta-functions different by as much as 20% from the October fitted values which means a very poor prediction. Hence, a thorough investigation has been performed to uncover the source of discrepancies.

CORRECTOR CALIBRATIONS

In short, LOCO uses gradient method and SVD to fit the modeled orbits to the measured data by varying the following variables

- Quadrupole errors
- Skew-quadrupole errors
- BPM calibrations
- BPM tilts
- Calibration of dipole correctors used to excite the orbit
- Corrector tilts

Hence, as the result of the fit one gets not only imperfections of the focusing (quadrupole and skew-quadrupole errors) but also important parameters of BPMs and dipole correctors (See e.g. Fig. 5 in Ref. [1]). In general, good convergence of the fit is obtained if the initial state of the model is close enough to the real machine. In other words, it is important to have good initial values for all variables.

Looking at the calibrations of horizontal correctors computed from data set 1 of February data (Figure 1) one notes two features: a) there is an offset of approximately 0.12 (which means that

these correctors are by 12% weaker than expected), b) two of the correctors have calibration errors close to 0.

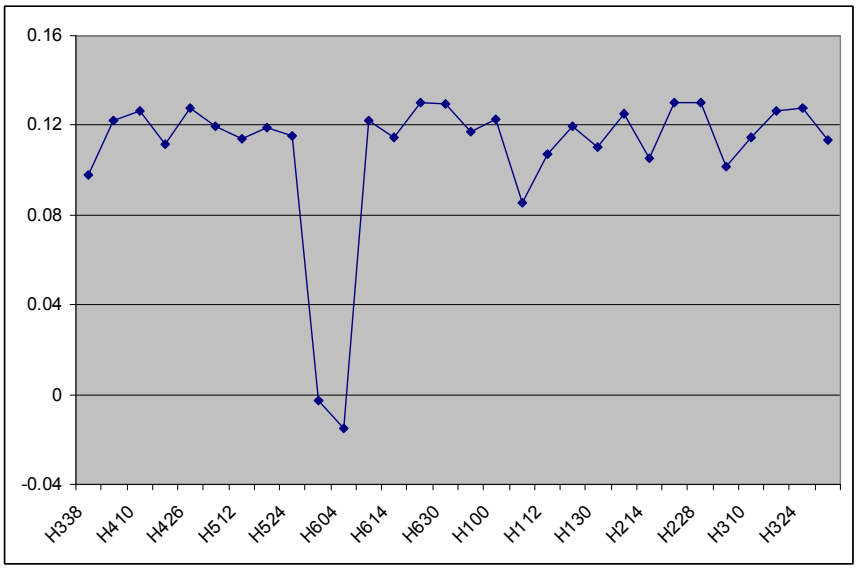

Figure 1. Calibration errors of horizontal dipole correctors calculated from 2/06 data set 1.

The first problem with average offset was tracked down to a bug in the fitting software. Namely, the horizontal correctors were assigned the kick of vertical correctors. However, fixing this bug did not affect the stability of solution. Most probably, scaling of all horizontal orbits by the same coefficient does not affect the fitting procedure.

The second feature proved to provide the solution. The two distinct correctors in Fig. 1 are the H602 and H604 which are the so-called LEP correctors. Recycler has four types of dipole correctors:

1. Regular horizontal, with kick calibration 117 μrad per 1 A of current
2. Regular vertical, 73 μrad/A
3. LEP horizontal, 143 μrad/A
4. LEP vertical, 116 μrad/A

Direct comparison of the measured orbits excited by regular correctors shows that their calibrations are close to the design values, while LEP correctors reveal large discrepancy (Figure 2). It appears that the horizontal LEP correctors are by 60% weaker than designed.

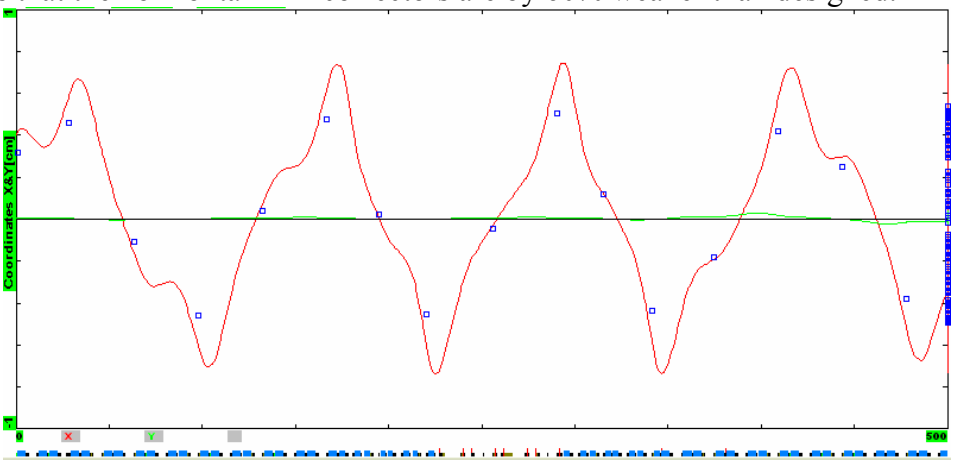

Figure 2. Orbit excited by H602 corrector (2A current). Dots – measurement, red line – calculation with design calibration of 142 μrad/A

It was later discovered that many, though not all, of the 'LEP' correctors show similar discrepancy. Because of large data redundancy it was natural to exclude these correctors from consideration which immediately made the fits converge. Results of the fits with all 'LEP' correctors excluded are presented below.

RESULTS

The February data were analyzed using data set 12 with the total of ~60 orbits. October data were not split into subsets which resulted in 173 orbits.

Figures 3 and 4 show the beta-functions calculated from the February and October optics files fitted to the corresponding ORM measurements. Note large (~20%) horizontal betatron wave in the October optics.

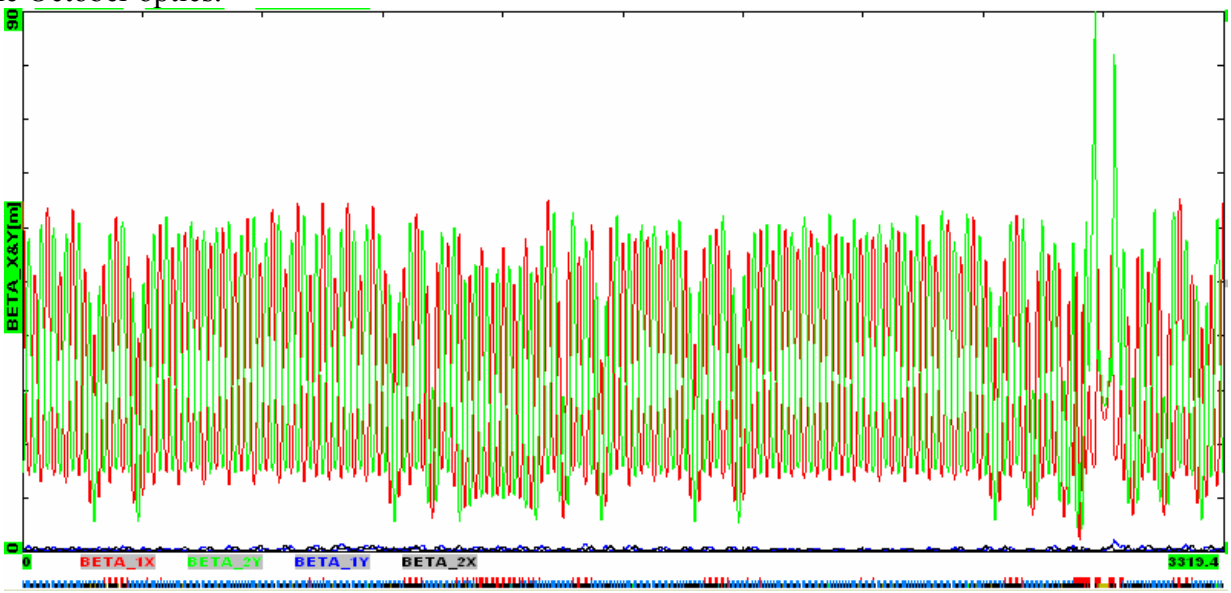

Figure 3. February 06 beta-functions. Qx=25.414, Qy=24.424.

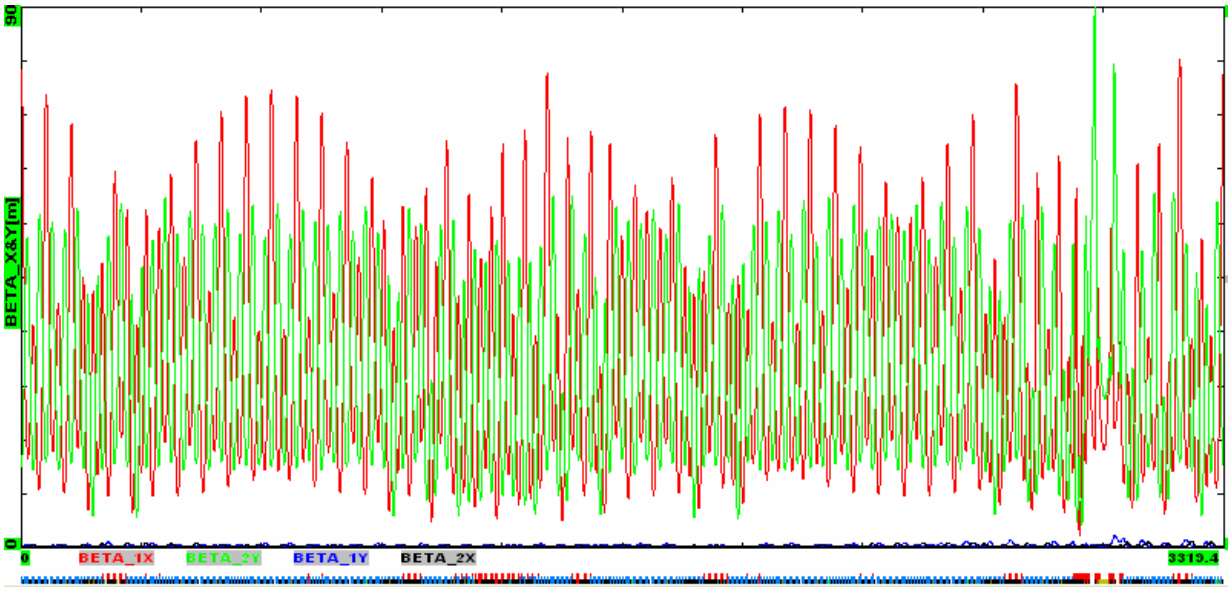

Figure 4. October 06 beta-functions. Qx=25.455, Qy=24.463.

Figures 5 and 6 represent the quality of the optics fitting. On the horizontal axis the BPM names are listed first horizontal then vertical. Each point then is the average difference between the measured and model orbit at the BPM in mm. Averaging is done over all orbits (60 in February and 173 in October). The typical resolution of Recycler BPMs is about 5-7 μm which means that in most cases the fit quality is only limited by the BPM accuracy. In Fig. 6 one can observe two groups of BPMs with larger than average error. These are the cooling section BPMs which are believed to have high noise as compared to the regular lattice.

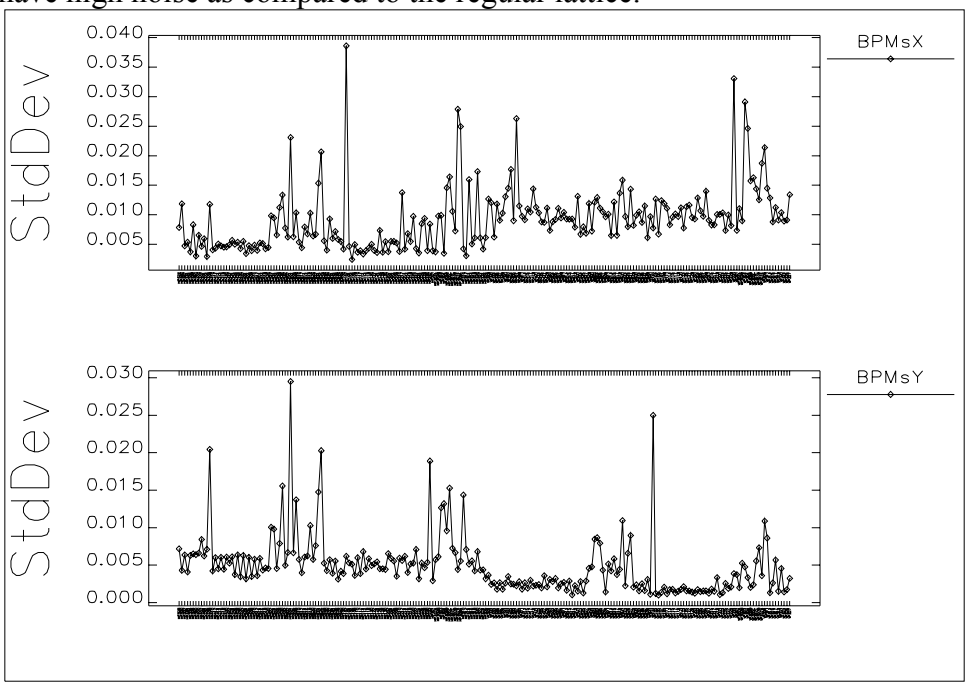

Figure 5. r.m.s. errors grouped by BPM for February data fit. Top – horizontal correctors, bottom – vertical correctors.

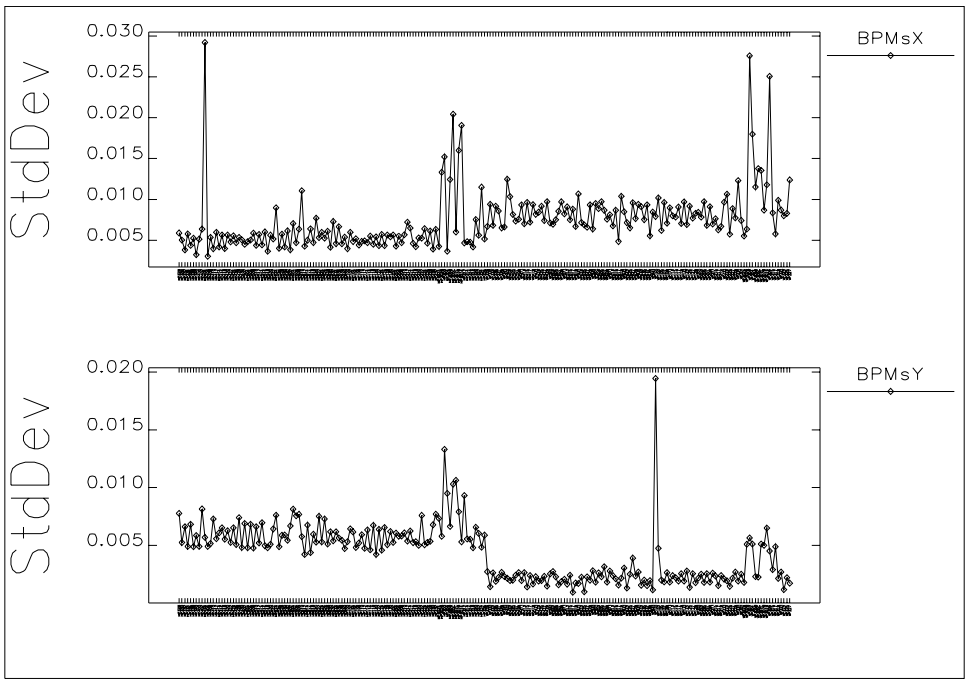

Figure 6. r.m.s. errors grouped by BPM for October data fit. Top – horizontal correctors, bottom – vertical correctors.

The OptiM lattice file created by M. Xiao contains measured parameters of all Recycler magnets. The main purpose of LOCO fit was to determine the real fields seen by the beam. In Figure 7 the relative errors of the quadrupole gradients are presented as found from the two sets of data. It is remarkable that all features of the February measurement are seen in October data as well.

Figure 8 presents the skew quadrupole fields in the units of integrated quadrupole strength (m*kGs/m). Skew quadrupole errors originate from tilts of quadrupoles and from vertical orbit in sextupoles. Hence, the difference in two measurements may be explained by the change of the closed orbit between February and October. Still, a large source of coupling at 404-407 locations is determined by both measurements.

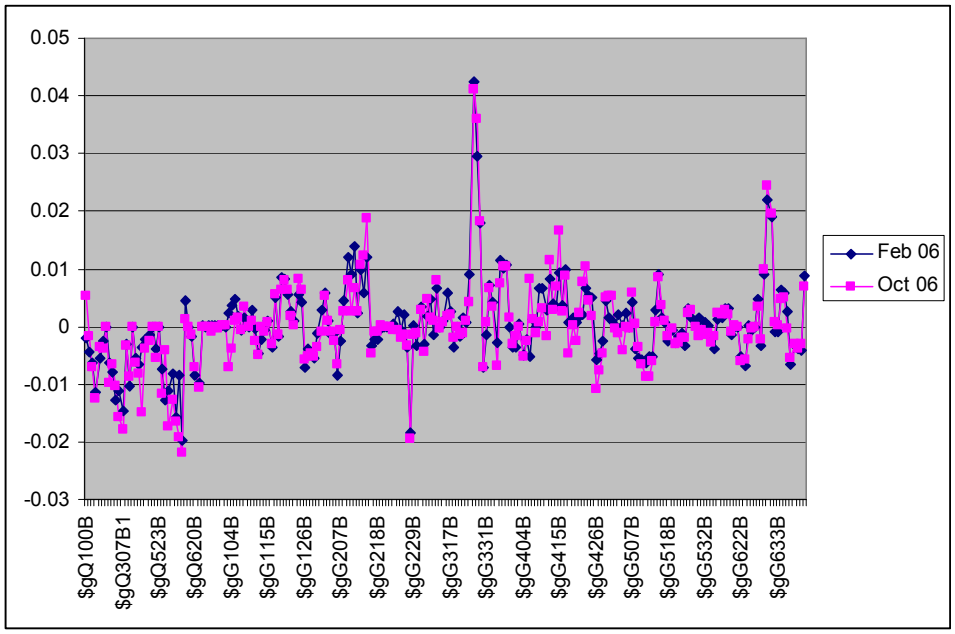

Figure 7. Quadrupole errors.

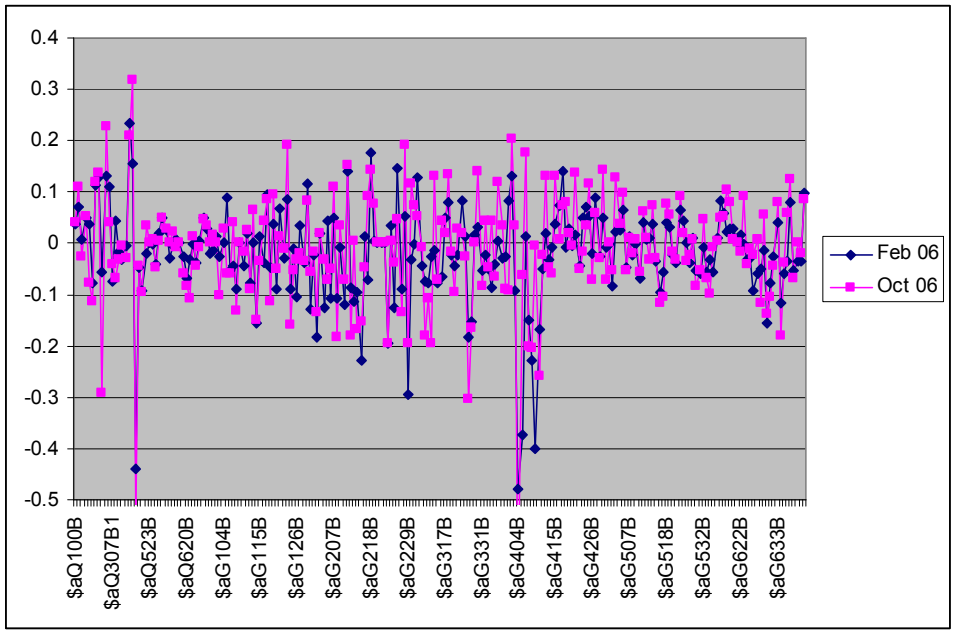

Figure 8. Skew quadrupole errors

One of advantages of LOCO is that it allows to measure the imperfections of the machine BPMs and dipole correctors, including their scale errors and tilts. In figures 9-10 the found parameters of BPMs are shown. The definition of the real orbit value of the coordinate is

$$X_{real} = X_{reported}(1+k)^{-1}$$

where k is the relative scale error shown on the plot. Again, excellent agreement between February and October data is observed. Corrector calibration errors obtained from the October data are shown in Fig. 11. Comparison with February results is not given because the corrector choise was different in the two cases. The fact worth mentioning is that the found corrector calibration is on average within 2% from the expected value.

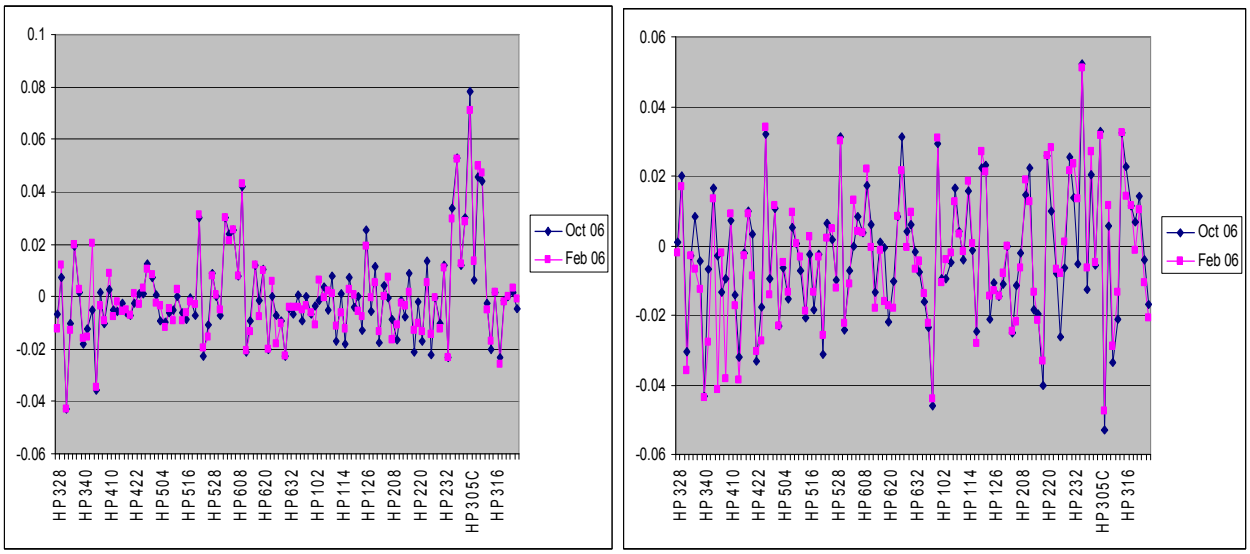

Figure 9. Horizontal BPM relative scale errors (left) and tilts in units of 90 degrees (right).

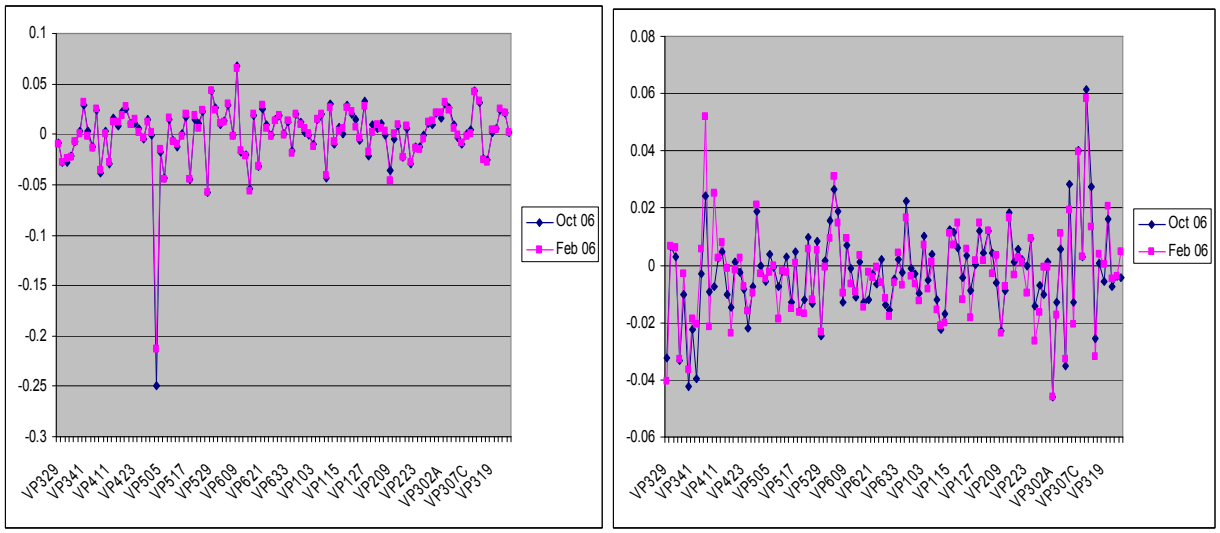

Figure 10. Vertical BPM relative scale errors (left) and tilts in units of 90 degrees (right).

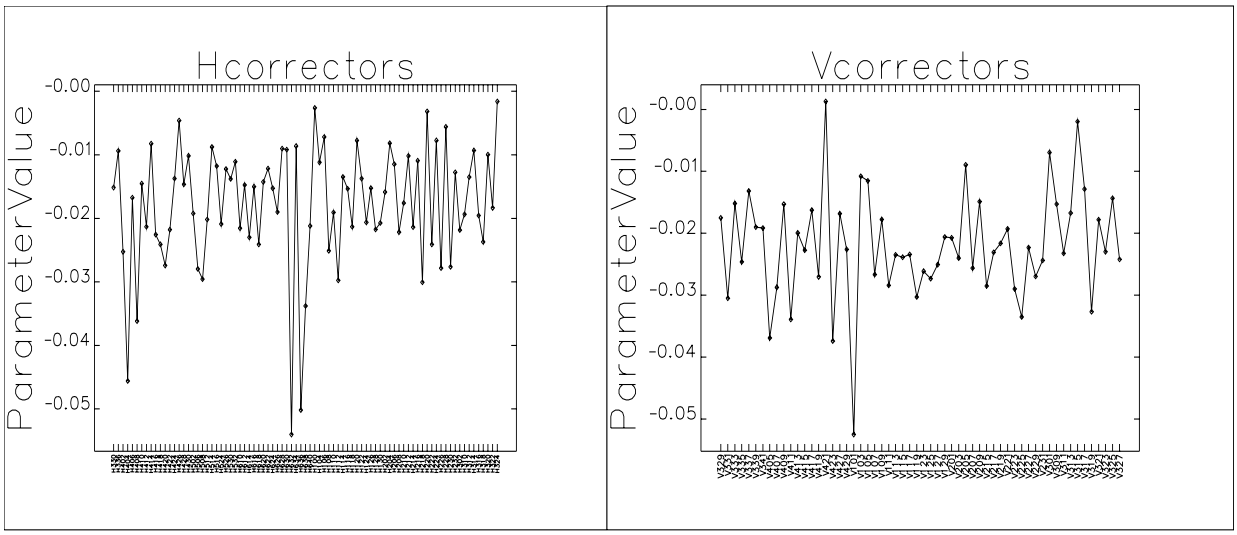

Figure 11. Horizontal (left) and vertical (right) corrector scale errors. October data.

CONCLUSION

Because of the grossly wrong calibration of the 'LEP' correctors used in the LOCO fitting of Recycler optics the found gradient errors contained features which do not exist in the machine. Although the beta-functions calculated using the incorrect gradient corrections were close to the correct solution (see Fig. 4 in Ref. [1]) the model was not usable for high precision prediction of the optics behavior. Namely, when the trim quadrupole and skew quadrupole settings were changed from February 2006 values to October values, the calculated tunes were as much as 0.02 off from the measured values and the beta-functions did not match by 40%. By eliminating the 'LEP' correctors from consideration the quality of the fit was highly increased. Figure 12 presents the comparison of beta-functions which were a) predicted by the February model with October power supply currents, b) measured in October. The accuracy of prediction is about 5%. The predicted tunes were within 0.003 from the measured values on top of 0.04 difference. The above mentioned facts allow to use the constructed optics file for high-precision corrections.

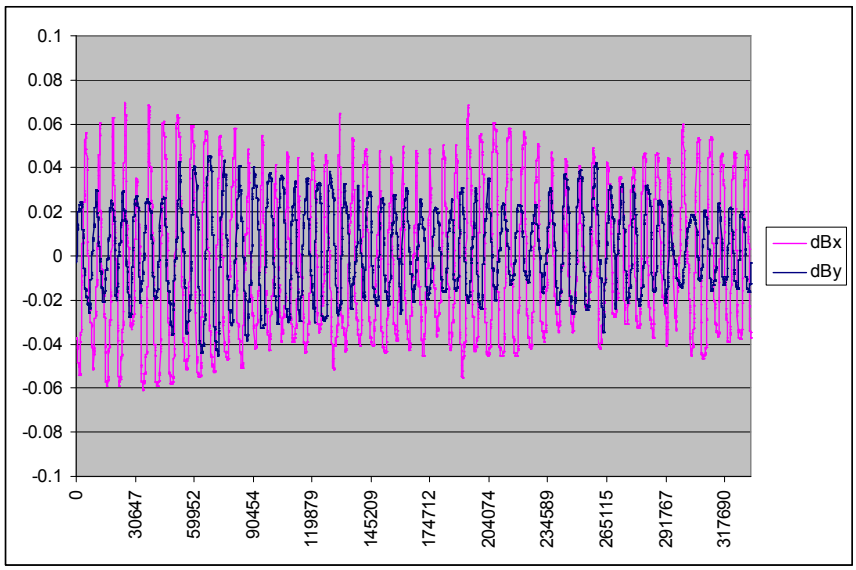

Figure 12. Relative difference between predicted and measured beta-function.

ACKNOWLEDGMENTS

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